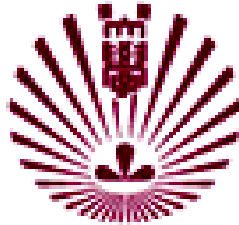


PHYSICAL PERFORMANCE AND DURABILITY EVALUATION OF RUBBERIZED CONCRETE



A DISSERTATION

Submitted to
Kyushu University
in partial fulfillment of the requirements
for the degree of
Doctor of Engineering

by

NURAZUWA BINTI MD NOOR

DEPARTMENT OF CIVIL AND STRUCTURAL ENGINEERING
GRADUATE SCHOOL OF ENGINEERING
KYUSHU UNIVERSITY

Fukuoka, Japan
September, 2014

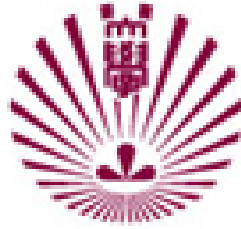
PHYSICAL PERFORMANCE AND DURABILITY EVALUATION OF RUBBERIZED CONCRETE

NURAZUWA BINTI MD NOOR

September, 2014

PHYSICAL PERFORMANCE AND DURABILITY

EVALUATION OF RUBBERIZED CONCRETE



A DISSERTATION

by

NURAZUWA BINTI MD NOOR

DEPARTMENT OF CIVIL AND STRUCTURAL ENGINEERING
GRADUATE SCHOOL OF ENGINEERING
KYUSHU UNIVERSITY
SEPTEMBER, 2014

ABSTRACT

The main objective of this research is to develop rubberized concrete with achievable structural strength using simple mix design. Simple mix design is a description by using the crumb rubber, used as in condition just received from the plant without any washing or pre-treating procedure. Then, three types of durability test were conducted namely, 1) Chloride ion diffusion test, 2) Abrasion wear resistance test, and 3) Freezing and thawing test. Up-to-date, many successful achievements were reported by researchers around the world. However, in Asian cases, very rare information on the use of wasted as a mixture component is gathered. By conducting this study, it could provide useful and valuable knowledge for construction technology especially for Asian industry. This dissertation consists mainly of the seven chapters.

In **Chapter 1**, the background, problem statement, significance, research contribution and novelty of this study are listed out.

In **Chapter 2**, research review on previous researchers work on the application of waste tire rubber in mortar/concrete and durability are described. Several important properties related to this study were viewed and discussed. High reduction in strength properties was observed by previous researchers and many suggestions were proposed either by washing the rubber or the use of suitable treatment on the rubber surface in order to enhance the bonding of the matrix. However, in my research, by using conventional mixing method, it was proposed that to use the rubber without any treatment (use directly as received) with maximum 20% sand replacement in volume is a method to use crumb rubber effectively. As a result, each rubberized mixture showed an acceptable structural strength value.

In **Chapter 3**, three step-by-step stages of mix design were conducted and discussed. The *first stage* was the preliminary study to determine the suitable waste tire rubber size and percentage replacement that can be used in rubberized mortar. Three rubber size group were received from the industry plant which were combination of 1mm-3mm, combination of 0.71mm-1.7mm and 0.425mm. Size of 1mm – 3mm with 10% of sand replacement was chosen in terms of acceptable fresh and hardened mortar properties. In *second stage*, suitable water-to-cement ratio (w/c) and required additional binder was determined before proceeding to concrete mix. Results shows that $w/c = 0.35$ gave reliable mortar physical properties. Finally, rubberized concrete with $w/c = 0.35$ was carried out and specimens were prepared for mechanical test and durability test. Along these three stages, air content was carefully studied and controlled.

In **Chapter 4**, experimental work and discussion on chloride ion diffusion in rubberized concrete tested by migration test and by immersion in salt water was described. Effective diffusion coefficient, D_e test was conducted according to JSCE-G571-2003. Meanwhile, immersion test in salt water was conducted according to JSCE-G572-2003. Additional concrete specimen with $w/c = 0.50$ was prepared to study the effectiveness of CR in high w/c in comparison with $w/c = 0.35$. Results showed that chloride transport characteristics were improved by increasing the amount of CR due to the fact that CR has the ability to repel water. Meanwhile, rubberized concrete with $w/c = 0.35$ gave better resistance against chloride ion compared to $w/c = 0.50$.

In **Chapter 5**, discussion on the effectiveness of crumb rubber to improve wear resistance tested by surface abrasion test was described. An experimental study on abrasion wear resistance was conducted on mortar ($w/c = 0.35, 0.30$ and 0.25) and concrete ($w/c = 0.35$) specimen containing CR with and without silica fume. From test results, it was clearly seen that 10% crumb rubber addition as sand replacement provide good resistance against abrasion. Meanwhile, compressive strength was the most important factor affecting the abrasion resistance, where abrasion resistance was increased with an increase in compressive strength. However, abrasion resistance was found to be slightly decreased when compressive strength exceeds 50N/mm^2 .

In **Chapter 6**, the role of crumb rubber as air void under freezing and thawing was studied. Specimen was prepared in three groups; first group was the specimen without silica fume with air content ranging between 4% to 5%, second group was the specimen without silica fume with air content ranging between 0% to 1.5% and third group was the specimen with silica fume with air content ranging between 4% to 5%. These rubberized concrete were tested on freezing and thawing resistance to understand this behavior. The temperature for freezing and thawing was set to $15^\circ\text{C} \pm 5^\circ\text{C}$ for thawing temperature and $-18^\circ\text{C} \pm 5^\circ\text{C}$ for freezing. This test was continued until 300 cycles according to ASTM C666. Results show that up to 300 freeze-thaw cycle, there was no minus effect observed for all specimen.

In **Chapter 7**, conclusions are drawn based on Chapter 4 to Chapter 6 and recommendations for future works is presented.

TABLE OF CONTENTS

ACKNOWLEDGEMENT	i
ABSTRACT	iii
TABLE OF CONTENTS	v
LIST OF TABLES	ix
LIST OF FIGURES	x
CHAPTER	
1. INTRODUCTION	
1.1 Background of study	1
1.2 Problem statement	2
1.3 Significance of study	2
1.4 Contribution and novelty	3
1.5 Outline dissertation	3
References	
2. A REVIEW ON THE APPLICATION OF WASTE TIRE RUBBER IN CONCRETE STRENGTH AND DURABILITY	
2.1 General	6
2.2 Classification of waste tire rubber	6
2.3 Silica fume as additional cementitious materials	8
2.4 Rubberized concrete mix design approaches	9
2.5 Fresh properties of rubberized concrete	10
2.6 Hardened properties of rubberized concrete	
2.6.1 Compressive strength of rubberized concrete	11
2.6.2 Mechanism of strength reduction	13
2.7 Concrete durability consideration	
2.7.1 Chloride ion diffusion	13
2.7.2 Surface abrasion wear resistance	14
2.7.3 Freezing and thawing resistance	14
2.8 Cost estimation	15
2.9 Conclusion	16
References	

3. MIX DESIGN AND STRENGTH CHARACTERISTICS OF RUBBERIZED CONCRETE

3.1	General	20
3.2	Waste tire rubber and other mix materials	21
3.3	Preliminary study	22
3.4	Rubberized mortar mix design	
3.4.1	Materials, mix proportion and specimen preparation	26
3.4.2	Fresh properties, strength development, density and relationship with elastic modulus	26
3.4.3	In-plane strain distribution by using digital image correlation method, DICM	31
3.4.4	Flexural strength	33
3.5	Rubberized concrete mix design	
3.5.1	Materials, mix proportion and specimen preparation	36
3.5.2	Fresh properties and strength development	36
3.5.3	Ultrasonic pulse velocity	41
3.5.4	Flexural strength and splitting tensile strength	42
3.6	Discussion	
3.6.1	Control of fresh properties in rubberized mortar and concrete	44
3.6.2	Evaluation of compressive strength with pore volume	46
3.7	Conclusion	46
	Reference	

4. RUBBERIZED CONCRETE DURABILITY AGAINST CHLORIDE ION PENETRATION

4.1	General	50
4.2	Experimental methodology	
4.2.1	Mix design	50
4.2.2	Mercury intrusion porosimetry, MIP	51
4.2.3	Chloride diffusion coefficient by migration test	52
4.2.4	Chloride diffusion coefficient by immersion in salt water	54
4.3	Porosity and pore size distribution	56
4.4	Effective diffusion coefficient of chloride ion under steady state condition,	

	D_e	58
4.5	Apparent diffusion coefficient of chloride ion under non-steady state condition, D_a	62
4.6	Discussion	
4.6.1	Effect of crumb rubber and silica fume on chloride ingress	64
4.6.2	Relationship between D_a and D_e	65
4.7	Conclusion	67
	References	

5. RUBBERIZED CONCRETE DURABILITY AGAINST ABRASION

5.1	General	69
5.2	Experimental methodology	69
5.3	Mortar surface resistance against abrasion	
5.3.1	Surface depth loss and weight loss	70
5.3.2	Effect of mortar strength on the abrasion resistance	74
5.4	Concrete surface resistance against abrasion	
5.4.1	Effect of crumb rubber on abrasion resistance	75
5.4.2	Effect of silica fume on abrasion resistance	75
5.4.3	Effect of water-to-cement ratio on abrasion resistance	76
5.4.4	Depth loss comparison between rubberized mortar and rubberized concrete mix	77
5.4.5	Depth loss percentage difference and relationship between compressive strength and depth loss	77
5.5	Discussion	
5.5.1	Abrasion resistance and compressive strength	80
5.5.2	Improvement of depth loss	81
5.6	Conclusion	82
	References	

6. RUBBERIZED CONCRETE DURABILITY AGAINST FREEZING AND THAWING

6.1	General	84
6.2	Experimental methodology	84

6.3	Initial temperature	85
6.4	Effect of crumb rubber in freezing and thawing resistance	
6.4.1	Dynamic modulus of elasticity, E_{dyn}	87
6.4.2	Relative dynamic modulus of elasticity, RDME	89
6.4.3	Ultrasonic pulse velocity, V	91
6.4.4	Compressive strength and weight loss	93
6.5	Discussion and conclusion	93
References		

7. CONCLUSION AND FUTURE WORK RECOMMENDATION

7.1	Conclusion	97
7.2	Future work and recommendation	98



PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

LIST OF TABLES

Table No		Page
Table 2.1	Advantage and disadvantage of using waste tire rubber as concrete constituent	6
Table 2.2	Waste tire rubber classification	7
Table 2.3	Chemical composition of mineral admixture	8
Table 2.4	Rubberized Concrete Mix Design Approaches By Previous Researchers	10
Table 2.5	Fresh properties of rubberized mortar/concrete reported by previous researchers	10
Table 2.6	Cost estimation	16
Table 3.1	Physical properties of materials	21
Table 3.2	Preliminary mortar flow result	23
Table 3.3	Fresh properties and rubber distribution of trial mix method	25
Table 3.4	Mix proportion of rubberized mortar	27
Table 3.5	Ratio of rubberized mortar flexural strength to compressive strength (%)	35
Table 3.6	Mix proportion of rubberized concrete	37
Table 3.7	Description of rubberized concrete mix	37
Table 3.8	Fresh properties of rubberized concrete	37
Table 3.9	Concrete quality by ultrasonic pulse velocity as recommended by JIS	41
Table 3.10	Details of chemical admixture and fresh properties of rubberized concrete	46
Table 3.11	Details of chemical admixture and fresh properties of rubberized mortar	45
Table 4.1	Mix design of rubberized concrete with $w/c = 0.50$	51
Table 4.2	Fresh properties of rubberized concrete with $w/c = 0.50$	51
Table 5.1	Mortar compressive strength	74
Table 5.2	Data of abrasion wear resistance at 4000 disc rotation for all mixture	79
Table 6.1	Percentage difference of compressive strength at 300 cycles	94

LIST OF FIGURES

Figure No		Page
Fig. 1.1	Frame layout of the dissertation outline	4
Fig. 2.1	Tire Rubber	7
Fig. 2.2	Illustration of weight for sand and crumb rubber	16
Fig. 3.1	Level of rubberized mix design	20
Fig. 3.2	Crumb rubber, CR	21
Fig. 3.3	Preliminary mortar mix	22
Fig. 3.4	Strength development of preliminary mortar mix at 28 water curing days	24
Fig. 3.5	Four trial mix method	25
Fig. 3.6	Series of rubberized mortar mix	27
Fig. 3.7	Rubberized mortar flow	29
Fig. 3.8	Rubberized mortar air content	29
Fig. 3.9	Strength development of rubberized mortar	29
Fig. 3.10	Fresh and hardened density of rubberized mortar	30
Fig. 3.11	Relationship between mortar compressive strength and static elastic modulus at 28 days	30
Fig. 3.12	Digital image correlation measurement device	31
Fig. 3.13	Mechanism of DIC capture image	32
Fig. 3.14	Strain on S1-35 due to 420kN compression load	34
Fig. 3.15	Strain on S4-35 due to 420kN compression load	34
Fig. 3.16	Crack pattern on rubberized mortar surface	34
Fig. 3.17	Stress-strain relationship of cube rubberized mortar at 14 days curing age	35
Fig. 3.18	Rubberized mortar flexural strength at 28 days	35
Fig. 3.19	Strength development of rubberized concrete without silica fume	38
Fig. 3.20	Strength development of rubberized concrete with silica fume	39
Fig. 3.21	Relationship between elastic modulus and compressive strength of rubberized concrete without silica fume	39
Fig. 3.22	Relationship between elastic modulus and compressive strength of rubberized concrete with silica fume	40
Fig. 3.23	Stress-strain curve of rubberized concrete	40
Fig. 3.24	Relationship between compressive strength and pulse velocity of rubberized concrete with and without silica fume	42

Figure No		Page
Fig. 3.25	Flexural strength of rubberized concrete at 28 days	43
Fig. 3.26	Splitting tensile strength of rubberized concrete at 28 days	43
Fig. 3.27	Concept of concrete and mortar	45
Fig. 3.28	Data of total pore volume derived by Rita	57
Fig. 4.1	Specimen preparation for porosity test	51
Fig. 4.2	Left; specimen under 2 days vacuum condition and right; mercury intrusion porosimetry, MIP equipment	52
Fig. 4.3	Specimen measurement for chloride diffusion by migration test	53
Fig. 4.4	Specimen preparation, left; Epoxy resin, middle; specimen covered with epoxy resin, and right; specimen sealed with silicon in the rubber case	53
Fig. 4.5	Vacuum process and migration cell with NaOH and NaCl solution	54
Fig. 4.6	Schematic diagram of migration cell	54
Fig. 4.7	Left; epoxy resin coating and right; specimen arrangement NaCl immersion	56
Fig. 4.8	Splitted specimen after spraying with silver nitrate ,AgNO ₃	56
Fig. 4.9	Powder from concrete slice	56
Fig. 4.10	Pore size distribution for rubberized concrete without silica fume (w/c = 0.50)	57
Fig. 4.11	Pore size distribution of rubberized concrete without silica fume (w/c = 0.35)	57
Fig. 4.12	Pore size distribution of rubberized concrete with silica fume (w/c = 0.35)	58
Fig. 4.13	Porosity of rubberized concrete at different percentage replacement	58
Fig. 4.14	Effective chloride ion diffusion coefficients and compressive strength at 28 days of rubberized concrete (w/c = 0.50)	59
Fig. 4.15	Effective chloride ion diffusion coefficients and compressive strength at 28 days of rubberized concrete (w/c = 0.35 without silica fume)	60
Fig. 4.16	Effective chloride ion diffusion coefficients and compressive strength at 28 days of rubberized concrete (w/c = 0.35 with silica fume)	60
Fig. 4.17	Relationship between compressive strength and effective chloride ion diffusion coefficient for mix with w/c = 0.35	61
Fig. 4.18	Relationship between compressive strength and effective chloride ion diffusion coefficient for mix with w/c = 0.50	61

Figure No		Page
Fig. 4.19	Chloride ion versus depth from surface for $w/c = 0.50$	62
Fig. 4.20	Chloride ion versus depth from surface for $w/c = 0.35$ (without silica fume)	63
Fig. 4.21	Chloride ion versus depth from surface for $w/c = 0.35$ (with silica fume)	63
Fig. 4.22	Apparent diffusion coefficient, D_a by percentage of crumb rubber replacement	64
Fig. 4.23	Porosity of mix without silica fume versus porosity of mix with silica fume	65
Fig. 4.24	D_e of mix without silica fume versus D_e of mix with silica fume	66
Fig. 4.25	Relationship between D_a and D_e	66
Fig. 5.1	Specimen preparation	70
Fig. 5.2	Dorry abrasion testing machine	71
Fig. 5.3	Silica sand	71
Fig. 5.4	Depth loss versus abrasion disc rotation of rubberized mortar at 28 curing days	72
Fig. 5.5	Weight loss versus abrasion disc rotation of rubberized mortar at 28 curing days	73
Fig. 5.6	Relationship between mortar depth loss and compressive strength at 4000	74
Fig. 5.7	Depth loss of rubberized concrete without silica fume due to abrasion load ($w/c = 0.35$)	75
Fig. 5.8	Depth loss of rubberized concrete with silica fume due to abrasion load ($w/c = 0.35$)	76
Fig. 5.9	Depth loss of rubberized concrete without silica fume due to abrasion load ($w/c = 0.50$ and 0.35)	76
Fig. 5.10	Depth loss comparison between rubberized concrete and rubberized mortar of $w/c = 0.35$	77
Fig. 5.11	Depth loss of concrete surface at 4000 rotation	78
Fig. 5.12	Depth loss percentage difference	79
Fig. 5.13	Relationship between rubberized concrete compressive strength and depth loss at 4000 disc rotation	80
Fig. 5.14	Depth loss improvement of rubberized mortar	81
Fig. 6.1	Temperature gage embedded in the concrete for initial temperature test	85

Figure No		Page
Fig. 6.2	Result of initial freezing temperature at every 15 minutes	85
Fig. 6.3	Result of initial thawing temperature at every 15 minutes	86
Fig. 6.4	Freezing and thawing manual apparatus	86
Fig. 6.5	Dynamic modulus of elasticity of Series 1 at 300 freeze-thaw cycle	87
Fig. 6.6	Dynamic modulus of elasticity of Series 1 and Series 2 at 300 freeze-thaw cycle	88
Fig. 6.7	Dynamic modulus of elasticity of Series 1 and Series 3 at 300 freeze-thaw cycle	88
Fig. 6.8	Relative dynamic modulus of elasticity of Series 1 at 300 freeze-thaw cycle	89
Fig. 6.9	Relative dynamic modulus of elasticity of Series 1 and Series 2 at 300 freeze-thaw cycle	90
Fig. 6.10	Relative dynamic modulus of elasticity of Series 1 and Series 3 at 300 freeze-thaw cycle	90
Fig. 6.11	Pulse velocity of Series 1 at 300 freeze-thaw cycle	91
Fig. 6.12	Pulse velocity of Series 1 and Series 2 at 300 freeze-thaw cycle	92
Fig. 6.13	Pulse velocity of Series 1 and Series 3 at 300 freeze-thaw cycle	92
Fig. 6.14	Surface condition after 300 freeze-thaw cycles	94

CHAPTER 1 INTRODUCTION

1.1 Background of study

Reinforced concrete is usually durable and cost effective and one of the most used structural materials. However, there are many structures which show early deterioration, especially those exposed to aggressive environment. It is well known that the durability of materials and structures depends both on the environmental condition and on the material resistance to the action of aggressive substance.

Reinforced concrete structures exposed to aggressive environment is susceptible to attack by simultaneous action of a number of physical and chemical deterioration processes [1]. For instant, the chemical action of seawater constituent of cement hydration products, alkali-aggregate expansion (when reactive aggregates are present), crystallization pressure of salt within concrete if one face of the structure is subject to wetting and other drying condition, frost action in cold climates, corrosion of embedded steel in reinforced or pre-stressed members due to chloride ion permeability, and physical erosion due to wave action and floating object.

The corrosion of reinforcing steel in concrete due to chloride transport in concrete structures in aggressive environment has received increasing attention in recent years because of its wide spread occurrence and the high cost of repair. The steel in concrete is protected by an oxide passive film generated in highly alkaline environment, although the corrosion cell is fully composed: cathodic molecules such as moisture and oxygen, anode, electrolyte and electric circuit. However, a build-up of chloride at the depth of steel accompanied by a local fall in the pH of the pore solution depassivates the protection film prior to steel corrosion [2]. To prevent the chloride permeation into concrete, the use of proper material which can minimize chloride transport to steel reinforcement is introduced.

One of the solution suggested is the use of waste tire rubber as partial replacement of fine aggregate. It was claimed that the addition of fibrous rubber to concrete improved shock wave abrasion, reduced heat conductivity and noise level, and increase resistance to acid rain. Moreover, the inclusion of small waste tire rubber cubes into concrete results in higher resilience, durability and elasticity. Hence, this paper proposed the use of waste tire rubber as concrete constituent namely as rubberized concrete to increase the durability of concrete structure in aggressive environment.

1.2 Problem Statement

As stated in the introduction, chemical and physical deterioration process is the main problem to concrete that exposed to aggressive environment. It can affect the durability of the concrete due to the chemical action of seawater constituent on cement hydration product, alkali-aggregate expansion, corrosion of embedded steel in reinforced or pre-stressed member and others. Many researchers have studied the durability of the concrete subjected to aggressive environment and there were ongoing study to discover the valuable findings for concrete structure. There are many ways to improve the durability of the concrete such as adding the pozzolanic material as cement replacement to enhance the strength of the concrete, steel reinforcement coating and cathodic protection.

On the other hand, one of the major environmental challenges the world is facing now is the increasing piles of waste tires which is not easily biodegradable even after a long period of landfill treatment. If this number of waste is not controlled it will lead to environmental hazard. The accumulation of used tires at landfill sites also presents the threat of uncontrolled fires, producing a complex mixture of chemicals harming the environment and contaminating soil and vegetation. This is considered as one of the major environmental challenge the world is facing because waste rubber is not easily biodegradable even after a long period of landfill treatment. Research has shown the utilization of these waste tires as concrete material (rubberized concrete) might improve the concrete characteristics. Study reported by G. Senthil Kumaran, Nurdin Mushule and M. Lakshmipathy in 2008 listed the advantages of rubberized concrete over ordinary concrete where it has good water resistance with low absorption, improved acid resistance, low shrinkage, high impact resistance, and excellent sound and thermal insulation.

In this research, it is assumed that the only deterioration mechanism of the concrete structure is that resulting from chloride ion penetration and erosion due to wave and other solid material in the sea. The used of waste tire rubber as concrete constituent in aggressive environment structure perhaps can improve these durability aspects by controlling the ingress of chloride into concrete and reduce the wear loss of the concrete.

1.3 Significance of Study

As Japan is developed country, it is expected that millions tones of tires wastes will be produced annually and usually been treated as waste disposal. In 2012, according to Japan Automobile Tire Manufacturer Association, 1.13 million ton of used tire is generated every year which is not biodegradable even after a long period of landfill treatment. These used tires are mostly used in fuel utilization industries, exporting industries and recycling industries. In the other hand, the abundant piles of waste can be reduce and utilize to minimize the green houses impact, uncontrolled fires and contaminating soil. For ensuring sustainable environment, all parties including government, researchers, industries as well as the publics should find the best solutions to utilize the generated waste product into

recycle materials. By using recycle tire rubber as concrete replacement materials; the most beneficial potential for the use of industrial by-product is the environmental values. This efforts will not only benefits to the government in reduction of providing land for disposal, but also increase the economy growth in various sectors especially amongst construction industry. Hence, the successful use of waste tire in concrete could provide one of the environmentally responsible and economically viable ways of converting this waste into valuable resource.

1.4 Contribution and Novelty

The main objective of this research is to develop rubberized concrete with achievable structural strength using simple mix design. Simple mix design is describe by using the crumb rubber directly as received from the plant without any washing or pre-treated procedure. Then, three types of durability test will be conducted namely,

1. Abrasion wear resistance test
2. Chloride ion diffusion test, and
3. Freezing and thawing test

Up-to-date, many successful achievements were reported by researchers around the world. However, in Asian cases, very rare information on the used tire as mixture component can be gathered. Hopefully by conducting this study, it could provide useful and valuable knowledge for construction technology especially for Asian industry.

1.5 Outline of Dissertation

Fig. 1.1 summarized the dissertation outline which composed of seven chapters as follows,

Chapter 1 describes the background of the study, its problem statement and the limitation of the study. It also lists the contribution of the study.

Chapter 2 review worked done by previous researchers on the application of waste tire rubber in mortar/concrete and durability. Several important properties related to this study were viewed and discussed.

Chapter 3 is the important chapter before durability testing could be conducted. There were three stages of mixing conducted and discuss. The first stage was the preliminary study to determine the suitable waste tire rubber size that can be used in rubberized concrete. Then, a second stage was conducted on mortar mix to determine the suitable water-to-cementitious ratio. Finally, rubberized concrete was carried out and specimens were prepared for mechanical test and durability test. Along these three stages, air content was carefully study and control.

Chapter 4 contains discussion on the effectiveness of crumb rubber to improve wear resistance

using surface abrasion test. Thus, an experimental study was conducted to see the behavior of crumb rubber with and without silica fume on abrasion wear resistance under different water to cement ratio for rubberized mortar and rubberized concrete.

Chapter 5 contains experimental work and discussion on chloride ion diffusion in rubberized concrete by migration test and also by immersion in salt water. Effective diffusion coefficient, D_e testing was conducted on 28 days water curing sample, meanwhile, for immersion in salt water testing, specimen were immersed for 3 month before apparent diffusion coefficient, D_a testing is conducted.

Chapter 6, this chapter describes the knowledge on the role of crumb rubber as air void. 22 rubberized concrete specimens with air-entrained and without air-entrained are tested on freezing and thawing resistance to understand this behavior. In addition, effect of silica fume on this behavior is also carried out.

Chapter 7, this chapter concluded the result obtained from Chapter 3 to Chapter 6. From these conclusions, future work are derived and recommended.

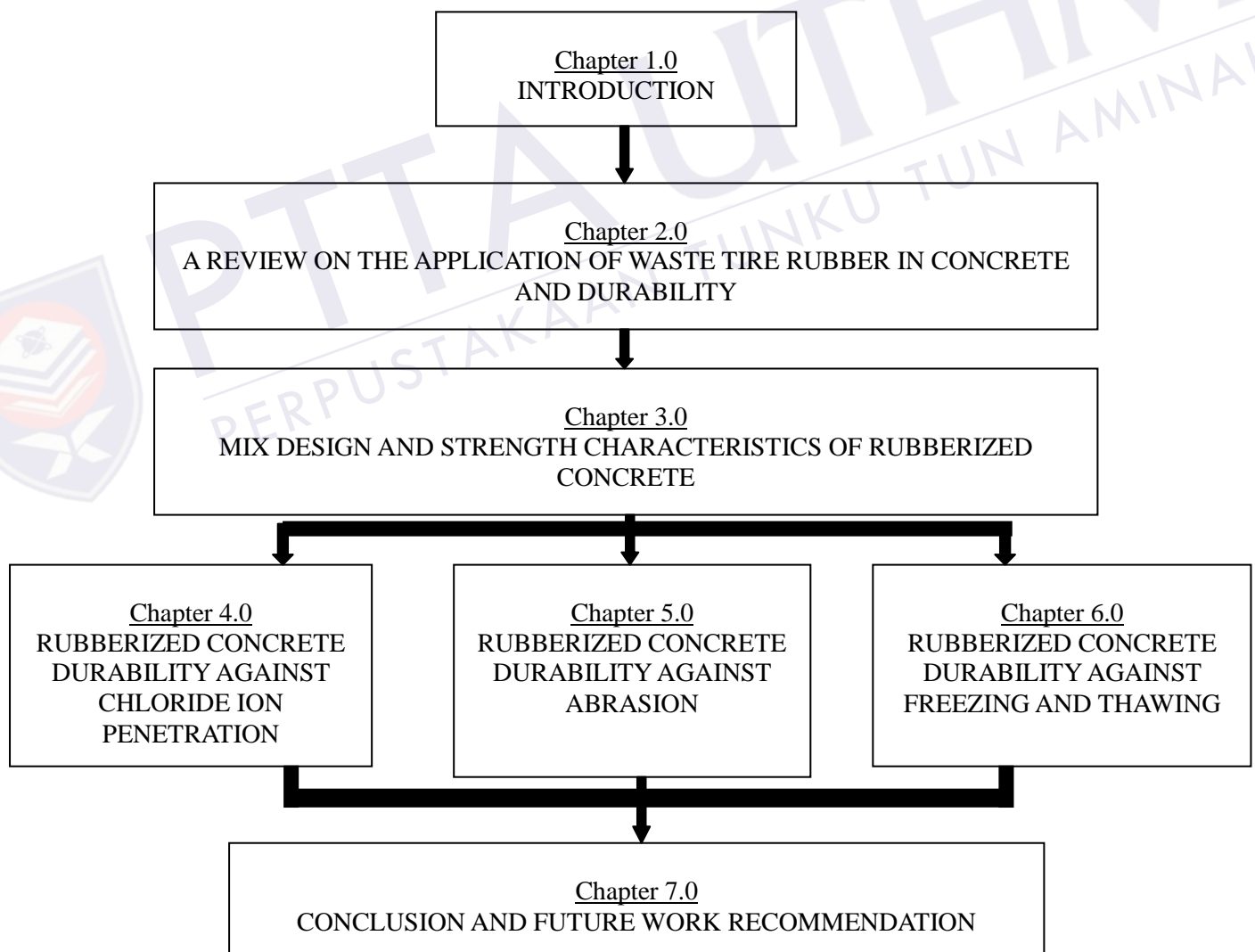


Fig. 1.1 Frame layout of the dissertation outline

Reference

1. Nagdi K, "Rubber as an Engineering Material:Guidelines for Users", Hanser Publication, (1993)
2. Page C.L., "Mechanism of Corrosion Protection in Reinforced Concrete Aggressive Structure", (1975).
3. G. Senthil, Kumaran Mushule and M. Lakshmipathy Nurdin, "A Reviews on Construction Technologies that Enables Environmantal Protection:Rubberized Concrete", American Journal of Engineering Applied Sciences 1(1), pp.41-45, (2008)



CHAPTER 2 A REVIEW ON THE APPLICATION OF WASTE TIRE RUBBER IN CONCRETE STRENGTH AND DURABILITY

2.1 General

Utilization of waste tire rubber in construction technology has been widely recognized in road and pavement engineering. However, the used of this by-product as mortar/concrete mixture component has been continued since early 90's. Up-to-date, many successful achievements were reported by researchers around the world and some of the benefits are summarized in Table 2.1 below.

Table 2.1 Advantage and disadvantage of using waste tire rubber as concrete constituent

Advantages	Disadvantages
1. Low unit weight (lightweight concrete)	10. Reduction in compressive strength
2. High resistance to abrasion	11. Low in tensile strength
3. High ductility	12. Low in flexural strength
4. Improve brittleness	
5. High resilience, durability and elasticity	
6. Absorbing the shocks and vibration	
7. Improve shrinkage and cracking	
8. Improve water permeability	
9. Good chloride ion penetration resistance	

2.2 Classification of Waste Tire Rubber

Waste tire rubber used as rubber aggregate in concrete can be classified based on the size of the rubber. Basically, there were five rubber aggregate classification as reported by Rafat Siddique and Tarun R. Naik [1] namely, scrap-tires, slit-tires, shredded/chipped tires, ground rubber and crumb rubber.

However, three broad categories of waste tire rubber which mainly utilized as concrete component are shown in Table 2.2 and Figure 2.1.

Table 2.2 Waste tire rubber classification [2]

Types	Size	Manufacturing method	Application in concrete
Shredded/ chipped	<u>Shredded</u>	Involved primary, secondary or both shredding operation	Gravel replacement
	Length : 300mm - 430mm 100mm - 150mm Width: 100mm - 230mm		
	<u>Chip</u> 13mm - 76mm	Involved primary and secondary shredding	
Crumb rubber	0.425mm - 4.75mm	1. Cracker mill process 2. Granular process 3. Micro-mill process	Sand replacement
Ground rubber	0.0075mm - 0.475mm	1. Magnetic separation 2. Screening	Cement replacement
Fiber rubber	Length: 8.5mm - 21.5mm	From shredded tire	Reinforced fiber
	Strips ≤ 8 mm long		



(a) Scrap-tire



(b) Slit-tire



(c) Shredded/chipped-tire



(d) Crumb rubber



(e) Ground rubber

Figure 2.1 Tire Rubber

[Source: (a),(b) Exemplar Fund LP homepage and (c) – (f) ECO Green Equipment homepage]

Specific gravity of the waste tire rubber ranges from 0.60 to 1.3 with the larger rubber having higher specific gravity followed by smaller rubber. Thus, due to the lower rubber specific gravity compared to other concrete component (cement, sand and gravel), it is expected that concrete containing rubber decrease the density of hardened concrete hence reduce the strength of the concrete.

2.3 Silica Fume as Additional Cementitious Materials

Silica fume, a by-product of the ferrosilicon industry, is a highly pozzolanic material that is used to enhance mechanical and durability properties of concrete. It may be added directly to concrete as an individual ingredient or in a blend of Portland cement and silica fume [3]. Eventhough silica fume is particularly expensive in Japan, it privileges cannot be ignored especially in concrete technology. Silica fume generally contain more than 90% silicon dioxide, SiO_2 which is very important to improve strength and durability due to its high reactive. JSCE recommended SiO_2 shall be not less than 85% to achieve concrete with good performance. List of chemical composition of silica fume and comparison with other mineral admixture, studied by various researchers are shown in Table 2.3.

Table 2.3 Chemical composition of mineral admixture

Chemical Composition	ASTM Type I ^[4] Cement	Silica Fume ^[4]	Fly Ash ^[5]	GBFS ^[6]	Metakaolin ^[4]
Silicon dioxide, SiO_2	20.1	93.71	64.6	34.39	20.1
Aluminium oxide, Al_2O_3	4.51	0.21	27.3	14.47	41.95
Ferric oxide, Fe_2O_3	2.5	0.31	2.2	0.63	0.52
Calcium oxide, CaO	61.3	0.35	1.5	41.67	0.34
Magnesium oxide, MgO	3.13	0.47	0.8	6.49	0.03
Sodium oxide, Na_2O	0.24	0.19	-	0.22	0.34
Potassium oxide, K_2O	0.39	1.19	1.5	0.36	0.11
Phosphorous oxide, P_2O_5	<0.9	0.14	-	-	0.28
Titanium oxide, TiO_2	0.24	0.01	-	0.53	1.74
Sulphur trioxide, SO_3	4.04	0.29	0.1	-	0.07
Loss of ignition	2.41	2.72	1.2	-	0.72

Research article written by Mehmet in 2007 reported the effects of using supplementary cementitious materials in binary, ternary and quaternary blends of fly ash (FA), ground granulated blast furnace (GGBFS) and silica fume (SF) on fresh and hardened properties of SCCs shows compressive strength reduction in mix incorporation of FA [7]. However ternary blends of SF and GGBFS provided a concrete with compressive strength of as high as 87 MPa exceeding that of control concrete even at 28 days of age. Combination of FA and crumb rubber in the mixture shows remarkably reduction in compressive strength [8]. Meanwhile, Mehmet reported that FA addition did not affected chloride ion

penetration result at 28 days but penetration decrease drastically up to 90 days. Also, FA helps to eliminated water sorptivity and absorption at certain percentage addition [9]. Erhan reported using crumb rubber in self-compacting concrete, SCC increased the need of superplasticizers, SP of the mixtures whereas with the use of FA a gradual fall was observed in the amount of SP used. Perhaps, study on Portland Cement-CR-SF can be looked into next seeing that SF gave good agreement when incorporated with the mix in SCC.

According to Concrete Library of JSCE, several advantages of using silica fume as binder in concrete are listed as follows,

1. Increase the strength
2. Improve the durability, and
3. Improve the placeability.

The suitable advisable ranges of silica fume replacement ratio differ for each purpose of use. As suggested by JSCE, the mostly ratio used ranging from 5 to 15% because ratio higher than this tends to lead to plastic shrinkage cracking and low resistance to frost damage [10]. ACI 234R-06 suggested that concrete with w/c of 0.35 to 0.45 may contains 3 to 10% silica fume by mass for durability enhancement and reduced chloride diffusivity in parking structures and bridge decks [3]. The maximum 10% percentage ratio was also supported by Microsilica-China for the same purposes as ACI 234R-06 and an additional increment up to 15% should be used by weight of cement as an addition not replacement. Meanwhile, Elkem Microsilica classifying it to several general recommendation dosages based on the application such as 7 to 10% for high strength concrete and low permeability, and 12 to 15% for underwater purposes. Thus, in this study, silica fume was selected between 10 and 15% of cement addition by weight. Only one ratio will be selected in rubberized concrete after several trial mixes in mortar.

2.4 Rubberized Concrete Mix Design Approaches

Currently, no standardized mixture procedure is documented either for Portland rubberized concrete (PRC) or self-compacting rubberized concrete (SCRC). Research is still ongoing to search for the best mix approaches for structural purposes. A review on mixing procedure was reported by Najim [11] and is tabulated in Table 2.4 below.

In this study, it is proposed to apply mixing procedure that commonly used in Japan to achieved rubberized concrete strength more than 40MPa. Seeing that substituting rubber aggregate in the concrete have tendency toward segregation and bleeding, has lead to several unusual adaptations of the conventional mixing procedure in an attempt to avoid this problem [12], the previous mixing procedure done by other researchers can be used as a guide. Thus, it was decided that preliminary study using mortar was important before concrete mix design stage, in order to understand the behavior on its fresh and hardened properties.

Table 2.4 Rubberized Concrete Mix Design Approaches By Previous Researchers

① <u>First Approaches</u>
All dry mix components such as coarse aggregate, fine aggregate and cement should first be mixed for between 1 minute and 5 minutes before gradually adding water, plus super plasticizers and SBR admixture if specified. Mixing should then continue for 3 to 5 minutes or until homogeneous.
② <u>Second Approaches</u>
First, dry mixing coarse aggregate and cement. Followed by gradually addition of rubber, fine aggregate and water with 75% super plasticizers. The remaining 25% of SP is then added during the final 3 minutes of the mixing process.
③ <u>Third Approaches</u>
Staggered addition of water where the coarse and fine aggregate, plus $\frac{1}{2}$ of the rubber aggregate are initially mixed with $\frac{1}{4}$ of the water. Cement is then added to the wet mix and further $\frac{1}{2}$ of the mixing water before gradually adding the remaining water. Mix for an additional 3-5 minutes.
④ <u>Forth Approaches</u>
For SCRC, all aggregates and cement are dry mixing for 30 seconds. Water with $\frac{1}{3}$ of SP is added and mix for 1 minute and 30 seconds. Finally, the residual quantity of SP (plus any water admixture, e.g. viscosity an/or air-entraining agents) are added and mixed for 210 seconds.

2.5 Fresh Properties of Rubberized Concrete

Table 2.5 summarized fresh properties of rubberized concrete/mortar that can be as guided in conducting this study.

Table 2.5 Fresh properties of rubberized mortar/concrete reported by previous researchers

No	Properties	Details
1	Flow/Slump	<p>Bigzonni reported self-compacting concrete mixes containing tyre wastes have good ability to flow and pass in the presence of obstacles [13]. However Topcu in his study reported a decreasing number or workability properties with low and high volume [14]. This was agreed by Khatib and Bayomy when they observed a reduction in slump with increasing rubber content by total aggregate volume. They also observed that mixtures made with fine crumb rubber were more workable than those with coarse tire chips or a combination of tire chips and crumb rubber.</p> <p>Erhan in 2009 reported the target slump flow was not executed at the concrete containing high amount of crumb rubber [8]. He also reported using crumb rubber increased V-funnel flow times and gradually increase with the increasing of crumb rubber. However using fly ash in the mixture resulted in a steady decrease of V-funnel flow with respects to the concrete without fly ash.</p>

No	Properties	Details
2	Unit Weight	Unit weight of concrete is decreased with the water to cement ratio and volume of rubbers. However, Nehdi reported the decrease almost negligible for rubber content lower than 10% to 20% of the total aggregate volume [15].
3	Air Content	It was reported that although no air-entrained used in the mixture, higher air content was measure as compared to control mixture made with air-entrained agent. This may due to non-polar nature of rubber particles and its ability to entrap air on jagged surface texture [16].

2.6 Hardened Properties of Rubberized Concrete

2.6.1 Compressive strength of Rubberized Concrete

Researches on utilizing the used tire rubber of vehicles as concrete material started in 1994 by Eldin and Ahmad Senouci focusing on strength characteristics [1]. High reduction in compressive strength due to the rubber leads to development of various methods to achieve the accepted structural strength level. Khatib in 1999 recommended rubber content should not exceed 20% of total aggregate volume in the mixture to avoid large number of strength reduction. Ali in 2008, suggested rubber concentration more than 25% are not recommended and Olkonomou in his studies on chloride ion penetration recorded 12.5% rubber replacement is the optimum percentage. Addition of 50% waste tyre rubber in self-compacting concrete mixture results in 48% to 58% strength reduction. Almost all researchers reported with the increasing amount and size of rubber in concrete mixture brings to the unit weight reduction. Furthermore, rubber tyre incorporated with the steel belt wires tyre and polypropylene fibers have positive effect on concrete strength and toughness which can be proposed for further research [17].

Using waste tyre rubber as replacement in concrete constituent brings to many advantages in concrete properties compared with ordinary concrete. However, the big issue playing in researchers mind is how to overcome the strength reduction of the rubberized concrete. Rubber tyre itself have tendency to entrap air in their rough surface and has ability to repel water in the concrete mixture, then a good bonding between cement paste and rubber cannot be achieved. Hence, the higher waste tyre rubber content in concrete mix will lead to decreasing of the unit weight of the mixture [R. Siddique and T.R Naik, 2004].

At early research stage on rubberized concrete, normal rubberized concrete studies resulted in non-structural concrete with water to cement ratio ranging from 0.3 to 0.68. Next an admixture was added to enhance the concrete strength. High cement content was proposed by Bignozzi (2006), Erhan (2010), Tayfun (2010) and Mehmet (2011) to produced high performance concrete which has high durability due to a low water-cement ratio. Research conducted by Bignozzi in 2006 shows a good

behavior of self-compacting rubberized concrete (SCRC) compared with ordinary Portland cement concrete but less behavior than ordinary self-compacting concrete (SCC). Plus, the use of slightly higher amount of superplasticizer in the mixture was recorded compared with SCC. However, poor concrete porosity was recorded by the presence of certain amount of rubber phase in comparison with ordinary SCC. Lower water to cement ratio up to 0.35 in the mixture was conducted in 2010 and 2011 by Erhan to enhance the SCRC behavior.

Another type of cement which can be considered is the magnesium oxychloride cement (Sorell's cement), combination of magnesium oxide and magnesium chloride solution. It is one of the strongest cement possessing certain advantages over Portland cement [18]. Biel and Lee discovered the good bonding with the fine rubber when magnesium oxychloride cement is used [19]. Using this type of cement, it is recommended the rubber content could be possible limited to 17% by volume aggregate for structural applications. But rubberized concrete using Sorell's cement are not widely studied.

A pre-treatment on rubber surface was introduced by immersion in sodium hydroxide (NaOH) solution for certain period. It is reported that rubber aggregate treated in NaOH solution for 20 minutes as coarse aggregate replacement improved abrasion resistance, water absorption flexural strength and fracture energy but with significant reduction in compressive strength [20]. Adhesive properties of SBR admixtures involves the use of carboxylic acids resulted in the strengthens bonding characteristics between hardened cement paste and rubber aggregate surface. Modulus elasticity for PRC can be improved by treating the rubber in sulphuric acid (H_2SO_4) [21]. In other approach, by pre-coating the rubber aggregate with cement paste and allowing to harden, before adding the rubber to the concrete mix, can increase the compressive strength by between 30% [16].

In addition, research conducted in 2004 had proposed treatment (NaOH) chip and fiber rubber with the interfacial bonding between the rubber and the cement paste matrix by drilling a 5 mm diameter hole through the rubber [Guoqiang Li, 2004]. It is found concrete contains treatment fiber with anchorage has higher compressive strength and stiffness compared with concrete contains treatment chips only. But it is suggested that the fiber length is restricted to less than 50 mm to avoid entangle. In the industry, there is no special equipment to cut waste tyre fiber and in this research it is suggested to further up the studies by developing suitable equipment. Meanwhile in 2008, underway research on fiber rubber (with an anchorage hole of different diameter) having size of 25, 50 and 75 mm x 7 mm x 7 mm was used as partial replacement of coarse aggregate in the concrete to developed a higher strength structural concrete member. [G. Senthil Kumaran, 2008]. Unfortunately, until now paper on this research findings has not been publish.

Latest, in 2013, research conducted by N.Ganesan et al. on self-consolidating rubberized concrete, SCRC beam-column joint pretreated the scrap rubber using PVA. The quantity of PVA was taken as 2.35% of water content and used for rubber surface treatment. The dense concrete was produced when the PVA undergoes polymerization reaction hence enhanced the interfacial bonding between the matrix and rubber particles. As result, 28 days compressive strength achieved 41.04 MPa

compared conventional self-consolidating concrete, SCC which was 52.89 MPa.

Thus in this study, the special part will be the rubber particles will be use directly without any washing procudere or pretreatment in order to produce concrete with achievable structural strength. The successful of this study depends on the several trial of mixing procedure.

2.6.2 Mechanism of Strength Reduction

The reduction of compressive strength of rubberized concrete may be due to the weak bonding between rubber particles and cement matrix. Khatib and Bayomy recognize three reasons for this strength reduction,

1. Rubber is much softer than the surrounding cement paste, when loading is applied, cracks are initiated quickly around the rubber particles due to the elastic mismatch.
2. The weak bonding between the rubber particles and cement paste, thus soft rubber particles may be view as voids in concrete which assumed to increase the air content in concrete and reduce the strength
3. The strength of the concrete depends greatly on the density, size and hardness of the conventional aggregates. By replacing certain amount of aggregate with low density of rubber particles, a reduction in strength is anticipated.

In this study, to get better understanding on mechanism of strength reduction, digital image correlation method test will be carried out. In addition, strain gage will be attached together on the specimen to get accurate result on this behavior.

2.7 Concrete Durability Consideration

2.7.1 Chloride Ion Diffusion

Chloride ion ingress into rubberized concrete was investigated to study the chloride ion profile in order to prevent the corrosion of the embedded steel reinforcing bar in the concrete. Due to the fact that rubber can repel water, it brings an interest to the researchers to explore the possibilities of rubber particles in providing resistance against chloride ion penetration. In 2007, Mehmet and Erhan study the effect of $w/c = 0.60$ and $w/c = 0.40$ on chloride ion permeability with inclusion of crumb rubber and tire chips under three designated rubber content of 5%, 15% and 25% by total aggregate volume. It was found that the chloride ion penetration depth depends on the amount of rubber used and curing time. However in this research, addition of 10% silica fume did not show any positive improvement with the inclusion of 25% rubber [9].

Rubberized mortar was then tested on chloride ion penetration in 2009 by Oikonomou and Mavridou. During this test, specimen was immersed in 3% of sodium chloride (NaCl) solution and in a sodium hydroxide (NaOH) solution separately. Results show reduction of 14.22% to 35.85% for

composition of 2.5% and 15% rubber aggregate respectively. Meanwhile composition 12.5% and 15% rubber aggregate shows almost similar values of electrical current passed through the samples. Thus, 12.5% has been chosen as the optimum percentages for further studies.

Chloride ion penetration resistance was conducted on SCRC containing fly ash in 2011. A progressive increase was observed in the test with the increase in rubber content without fly ash. Addition of fly ash did not affect the chloride ion permeability at 28 days, but penetration decrease dramatically when the curing period was extended to 90 days. In addition, substituting cement with certain percentage of amount in SCRC slightly eliminating porosity hence reduced water sorptivity and water absorption [Güneyisi, 2011]. This shows that the used of fly ash at 90 days helps reducing the chloride ion penetration rate into the SCRC. These results can guide further research especially on structure exposed to aggressive environment where high resistance to chloride ion penetration is needed.

Meanwhile in 2012, Miguel and Jorge de Brito conducted test with used tyre rubber aggregate ranging from 5% to 15 % at 5% increment. Rubber was added as fine aggregate, coarse aggregate and combination of fine and coarse aggregate. Similar with test conducted Mehmet in 2007, the effectiveness of rubber in reducing chloride ion penetration depending on curing time. In addition, it stated that the resistance became worsen with the increasing size of rubber however in combination of fine and coarse rubber aggregate, it improved with the increment of replacement ratio [23]

From previous study, rubber was added up to 25% on chloride ion penetration test and it shows that up to 25% addition did not gave significance effect on the chloride ion resistance. This behavior is similar with the addition of 10% silica fume in 25% rubber. Thus, in this study, concrete with maximum 20% crumb rubber replacement were tested on chloride ion diffusion test incorporated with silica fume in order to get an effect at 28 days specimen age.

2.7.2 Surface Abrasion Resistance

The effectiveness of crumb rubber to improve wear resistance using surface abrasion test was conducted in this study. Abrasion resistance mainly considered on the structure exposed to the heavy environment such as sea wave. The rate of wearing loss depending on the type and size of abrasion material and also loading pressure towards the concrete surface. Wearing can cause spalling of the concrete surface which in worsen cases due to the larger spalling volume, embedded steel reinforcing bar can be seen and if this steel bar is not protected, it could lead to the corrosion. Research done by Filipe Valadares et al.[25] on various rubber replacement ratio and size shows significant benefit in enhancement of abrasion resistance. Thus, an experimental study was conducted to see the behavior of crumb rubber with silica fume on abrasion wear resistance under different water to cement ratio.

2.7.3 Freezing and Thawing Resistance

Eldin and Senouci in 1994, conducted freezing and thawing test on non air-entrained concrete

which contains chip rubber as coarse aggregate replacement and crumb rubber as fine aggregate replacement. It was found that dynamic modulus of elasticity decreased during freezing and thawing cycles compared to control concrete. Result also suggested that the replacement of coarse aggregate cause more reduction than that fine aggregate replacement which concludes that small particle can resist freezing and thawing cycle better than larger rubber particle size [25].

Meanwhile, Savas in 1996 conducted the test on ground tire rubber as cement replacement shows that 10 and 15% replacement exhibit durability factors higher than 60% after 300 freezing and thawing cycles. However, replacement of 20% and 30% did not meet minimum acceptable limit by ASTM C 666 [15]. Then, from this test, it also showed that scaling increased with the increase of freezing and thawing cycles and amount of ground rubber in concrete, resulted in weight reduction.

Thus, in this study, behavior of crumb rubber by 10%, 15% and 20% fine aggregate replacement will be conducted to increase the freezing and thawing resistance of rubberized concrete compared to current result achievement by other researchers. Testing will be conducted according to ASTM C 666, Test Method for Resistance of Concrete to Rapid Freezing and Thawing.

2.8 Cost estimation

Basic cost estimation is presented based on the price of sand and crumb rubber. Cost of concrete mainly depends on

1. Strength of the concrete
2. Fresh properties performance
3. Chemical admixture
4. Mineral admixture

Total cost for concrete with w/c of 0.50 is around ¥10,000/m³. This amount is increasing with the decreasing of w/c. As for w/c of 0.35, no data is provided for 1m³ due to the rare used in the construction industry except for certain high structural performance. Special chemical admixture is needed when w/c below than 0.40 is used and consistent with its high performance, this special chemical admixture is expensive compared to ordinary chemical admixture.

By considering the scope of w/c=0.35 without silica fume, 1m³ of sand is around ¥3,500 and crumb rubber is ¥50/kg. When sand is divided by its density, price for 1kg sand becomes ¥9.03. Thus, for 1 cylindrical specimen with size of Ø100mm x 200mm, the volume, V_C is calculated as 0.00157m³. Based on Table 3.6, required volume sand, V_S for control was 741kg/m³, meanwhile when 20%CR is added, sand was reducing to 594kg/m³ (V_S) with CR volume, V_{CR} of 67kg/m³. Calculation of total sand and CR is illustrated in Fig. 2.2 below.

Total price for each case is tabulated in Table 2.6. It can be concluded that when 20% CR is

added in the mixture, price of fine aggregate increase 25%. Reason of this increment may be due to the manufacturing of the scrap tire into required tire size and process is costly since scrap tire undergo the cracker mill process, granular process and micro-mill process in order to produce crumb rubber. However, in terms of long term environment preservation and positive benefits in concrete durability performance, use of crumb rubber is worthwhile.

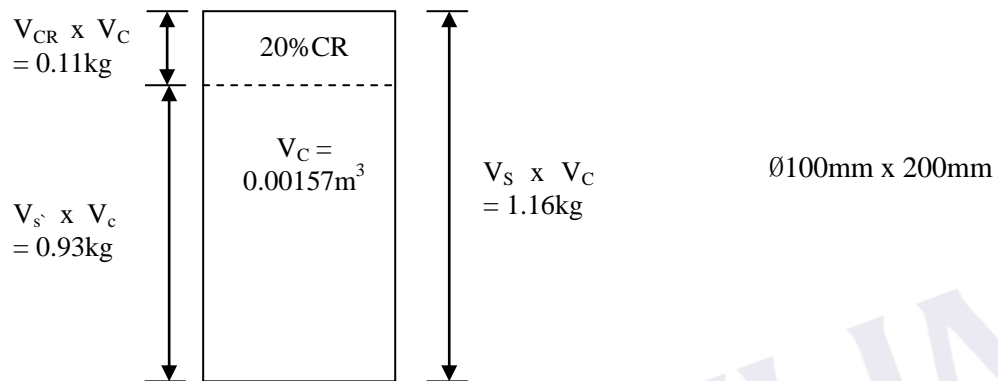


Fig. 2.2 Illustration of weight for sand and crumb rubber

Table 2.6 Cost estimation

No	Case	Cost estimation
1	100% sand	$= 1.16 \text{ kg} \times \text{¥}9.03/\text{kg} = \text{¥}10.47$
2	80% sand + 20% CR	<p>a. Sand</p> <p>$= 0.93\text{kg} \times \text{¥}9.03/\text{kg} = \text{¥}8.40$</p> <p>b. Crumb rubber</p> <p>$= 0.11\text{kg} \times 50/\text{kg} = \text{¥}5.50$</p> <p>c. Total</p> <p>$= \text{¥}8.40 + \text{¥}5.50$</p> <p>$= \text{¥}13.9 \text{ for } 0.00157\text{m}^3 \text{ cylindrical specimen}$</p>

2.9 Conclusion

By reviewing previous research, several conclusion can be made as follows;

- (1) Strength properties was decreased with the inclusion of rubber in concrete and bonding was improved by pre-treating the rubber surface with chemical solution such as NaOH.
- (2) Strength behavior should be importantly addressed in this study.
- (3) Chloride ion penetration resistance was improved when rubber was added in concrete, however, the resistance was decreased with over 25% rubber addition.

- (4) Abrasion resistance was also enhanced with the presence of rubber in concrete.
- (5) Freezing and thawing test shows good durability factor for rubber addition of 10% and 15%.
- (6) Thus, in this study, rubber was limited up to 20% addition in order to study the performance of rubberized concrete durability when rubber particles were used without pre-treating of the rubber surface.



Reference

1. R. Siddique, T.R. Naik, "Properties of Concrete Containing Scrap-Tire Rubber - An Overview", *Waste Management*, Vol. 24, pp. 563 – 569, (2004)
2. E. Ganjian, M. Khorami and A.A Maghsoudi, "Scrap-Tire-Rubber Replacement for Aggregate and Filler in Concrete", *Construction and Building Materials*, Vol. 23, pp. 1828 – 1836, (2009)
3. "Guide or the Use of Silica fume in Concrete" Report of ACI 234R-06, (2006)
4. M.H. Zang, V.M.Malhotra, " Characteristics of Thermally Activated Alumino-Silicate Pozzolan Materials and Its Use in Concrete", *Cement and Concrete Research*, Vol.25, No.8, pp.1713-1725, (1995)
5. G.C.Isaia, A.L.G.Gastaldini, R. Moraes, " Physical and Pozzolan Action of Mineral Addition on the Mechanical Strength of High-Performance Concrete", *Cement & Concrete Composites*, Vol, 25, pp.69-76, (2003)
6. T.W. Cheng, J.P. Chiu, " Fire Resistant Geopolymer Produced by Granulated Blast Furnace Slag", *Mineral Engineering*, Vol.16, pp.205-210, (2003)
7. Mehmet Gesoğlu and Erdoğan Özbay, "Effect of Mineral Admixtures on Fresh and Hardened properties of Self-Compacting Concretes: Binary, Ternary and Quaternary Systems", *Materials and Structures*, pp.923-937, (2007)
8. Güneş and Erhan, " Fresh Properties of Self-Compacting Rubberized Concrete Incorporated with Fly Ash," *Material and Structure*, pp.1037-1048, (2009).
9. Mehmet Gesoğlu and Erhan Güneş, "Strength Development and Chloride Penetration in Rubberized Concretes With and Without Silica Fume", *Materials and Structure*, Vol. 40, pp. 953-964, (2007)
10. Güneş Gesoğlu and Erhan Mehmet, "Permeability Properties of Self-Compacting Rubberized Concrete" *Construction and Building Materials*, pp.3319-3326, (2011).
11. "Recommendation for Design and Construction of Concrete Structures Using Silica Fume in Concrete-Draft", Translation from the Concrete Library, No.80, JSCE, (1998)
12. K.B Najim and M.R Hall, "A Review of the Fresh/Hardened Properties and Applications for Plain-(PRC) and Self-Compacting Rubberised Concrete (SCRC)", *Construction and Building Material*, pp.2043-2051, (2010).
13. G. Senthil, Kumaran Mushule and M. Lakshmipathy Nurdin, "A Reviews on Construction Technologies That Enables Environmental Protection: Rubberized Concrete", *American Journal of Engineering Applied Sciences* 1(1), pp.41-45, (2008).
14. M.C. Bigozzi and F. Sandrolini, "Tyre Rubber Waste Recycling in Self-Compacting Concrete", *Cement and Concrete Research*, pp.735-739, (2006).
15. Topçu Uygunoğlu and İ. B.Tayfun, "The Role of Scrap Rubber Particles On The Drying Shrinkage and Mechanical Properties of Self-Consolidating Mortars", *Construction and Building Materials*,

- pp.1141-1150, (2010).
16. Moncef Nehdi and Khan Ashfaq, "Cementitious Composites Containing Recycled Tire Rubber: An Overview of Engineering Properties and Potential Applications", *Cement, Concrete and Aggregates*, pp.3-10, (2001).
 17. Guoqiang Li, A. Stubblefield, G. Garrick, E. John, C. Abadie and B. Huang Michael, "Development of Waste Tire Modified Concrete", *Cement and Concrete Research*, pp.2283-2289, (2004)
 18. Mathur Misra and Renu A.K., "Magnesium Oxychloride Cement Concrete", *Indian Academy Science*, pp.239-246, (2007)
 19. Biel and D. Timothy, Biel and Lee., "The 3rd Materials Engineering Conference", pp. 351-358, San Diego, (1994).
 20. Colom X., "Structural and Mechanical Studies on Modified Reused Tyres Composites" *Europe Polymer Journal*, pp.2369-2378, (2006)
 21. Miguel Bravo and Jorge de Brito, "Concrete Made With Used Tyre Aggregate : Durability-related Performance", *Journal of Cleaner Production*, Vol. 25, pp. 42-50, (2012)
 22. N. Ganesan, B. Raj. and A.P. Shashikala. " Behavior of Self-Consolidating Rubberized Concrete Beam-Column Joints", *ACI Materials Journal*, Vol.110, No.6, pp.697-704, (2013)
 23. Filipe Valadares, Miguel Bravo and Jorge de Broti, "Concrete With Used Tire Rubber Aggregates: Mechanical Performance", *ACI Material Journal*, Vol. 109. Pp. 283-292, 2012
 24. Neil N. Eldin and A.B. Senouci, "Measurement and Prediction of the Strength of Rubberized Concrete", *Cement & Concrete Composites*, Vol.16, pp. 287-298, (1994)

CHAPTER 3 MIX DESIGN AND STRENGTH CHARACTERISTICS OF RUBBERIZED CONCRETE

3.1 General

Generally, this chapter focusing on mix design as summarized in Fig. 3.1 below. Preliminary study was conducted in order to select suitable rubber size as mixture component in mortar and concrete. This stage is very important to develop understanding on the behavior of mortar mix in-terms of compressive strength and workability when rubber is added. From this pre-study result, rubberized mortar mix design was further conducted as a benchmark for concrete mix design. Before discussing further on the mix design, properties of mixture component for all mixture were listed in Clause 3.2.

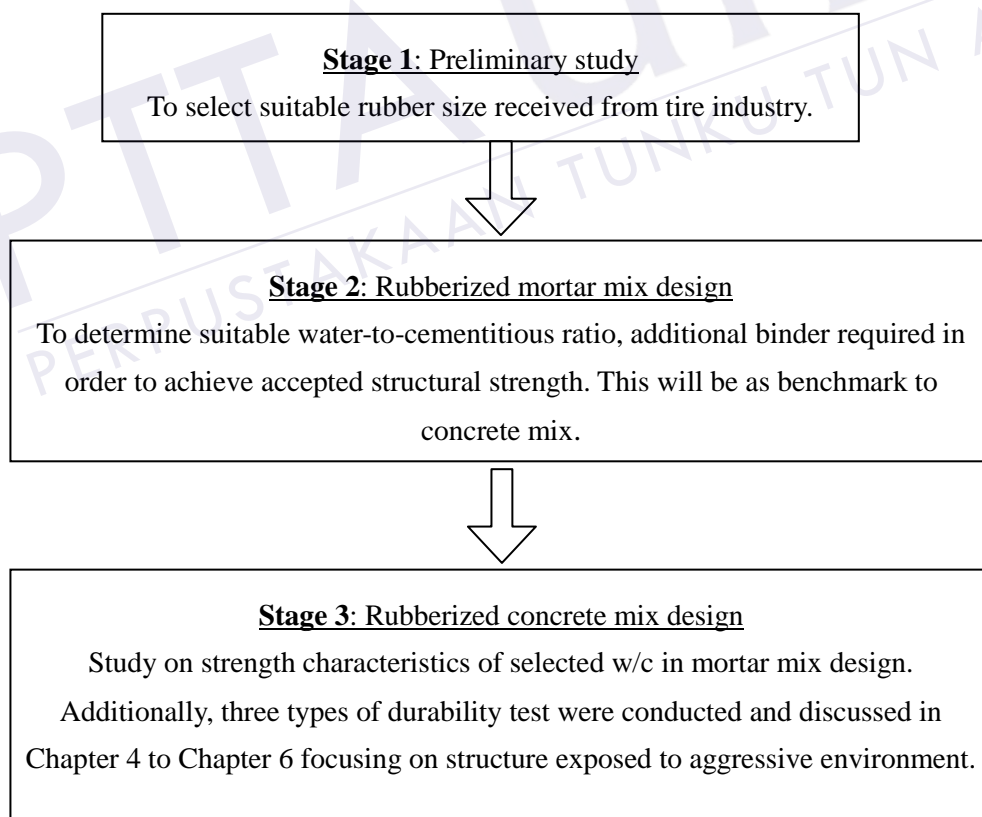


Fig. 3.1 Level of rubberized mix design

3.2 Waste Tire Rubber and Other Mix Materials

The waste tire rubber in this experiment was classified as crumb rubber, CR [1] which is by-product produced from used tire of vehicles (car, truck, etc.). The size of the selected CR was combination of 1mm - 3mm with density of 1.17 g/cm^3 and was used directly as received from recycle plant without any washing procedure as shown in Fig. 3.2.

Ordinary Portland cement (OPC) and silica fume (SF) with density of 3.16 g/cm^3 and 2.20 g/cm^3 respectively were used as binder. Sea sand passing 5mm sieve with density of 2.58 g/cm^3 and water absorption of 1.72 % which was less than 3.5% as stated in JIS standard was used as fine aggregate. Meanwhile, crushed stone with 20mm maximum size was used as coarse aggregate. All aggregate were prepared under saturated surface dry condition.

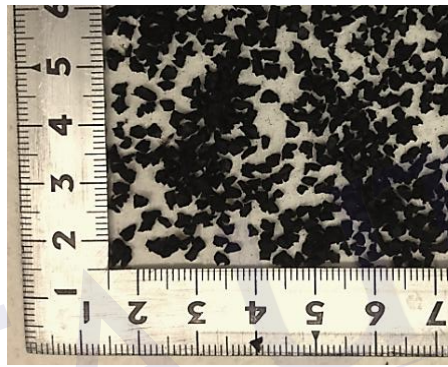


Fig. 3.2 Crumb rubber, CR

Table 3.1 Physical properties of materials

Component	Physical properties	
Ordinary Portland Cement	Density, g/cm^3	3.16
Silica fume	Density, g/cm^3	2.20
Crumb Rubber	Density, g/cm^3	1.17
Fine Aggregate	Density, g/cm^3 (SSD condition)	2.58
	Water absorption (%)	1.72
	Fineness modulus	2.77
Coarse Aggregate	Density, g/cm^3	2.91
Ether-based polycarboxylate superplasticizer	Density, g/cm^3 at 20°C	1.07
Air entraining agent	Density, g/cm^3	1.04
Air-modifying agent	Density, g/cm^3	1.00

Furthermore, ether-based polycarboxylate superplasticizer having density ranging from 1.05 – 1.09 g/cm³ at 20°C was added in both mortar and concrete mixed for workability measurement. The use of the superplasticizer varies depending on the conditions such as temperature thus trial mixes were done in the range of 1.0% to 5.0% of binder weight. As for air content, it was controlled by using air-entrained agent (to increase air content) and air-modifying agent (to reduce air content). Table 3.1 shows details of physical properties of mix components used in this study.

3.3 Preliminary Study

In preliminary study, three rubber size group were received from the industry plant which where combination of 1mm-3mm, combination of 0.71mm-1.7mm and 0.425mm. Size of 0.425mm was used at 0%, 5%, 15% and 25% of cement replacement; meanwhile, other sizes were used as sand replacement at the same replacement percentage. Four stages of water-to-cementitious were selected from 0.25, 0.30, 0.35 and 0.40 and total of 16 mortar bar specimen were prepared according to JIS mortar bar for each rubber size group as shown in Fig. 3.3. However, due to the lack of raw material for rubber size 0.425mm, mix was prepared only for w/c = 0.40 and 0.35.

		Rubber size			
		1mm - 3mm	0.71mm - 1.7mm	0.425mm	
Water to cementitious ratio	0.40	0%	A1	B1	C1
		5%	A2	B2	C2
		15%	A3	B3	C3
		25%	-	B4	C4
	0.35	0%	A5	B5	C5
		5%	A6	B6	C6
		15%	A7	B7	C7
		25%	A8	B8	-
	0.30	0%	A9	B9	-
		5%	A10	B10	-
		15%	A11	B11	-
		25%	A12	B12	-
	0.25	0%	A13	B13	-
		5%	A14	B14	-
		15%	A15	B15	-
		25%	A16	B16	-

Fig. 3.3 Preliminary mortar mix

In this preliminary study, 1.2% of chemical admixture dosage was used in all mixture to measure the ease of workability of rubber mixture. Result are tabulated in Table 3.2 and it can be

concluded that workability decrease under three following condition,

1. Increasing of binder content
2. Increasing of rubber content
3. Reduction of rubber size

However, a clear relationship cannot be seen for 0.425mm mixture due to the limited mixed in this pre-study. Thus, it was decided that rubber as cement replacement was excluded for further consideration even though compressive strength shows slightly increment compared to other sizes. In addition, author personal experience having difficulty in handling the rubber due to its finer size strengthens the decision made.

Fig. 3.4 shows compressive strength result for all mixture at 28 days water curing. As expected, low water-to-cementitious ratio enhanced the strength due to the higher binder in the mixture for 1mm-3mm resulted in large strength reduction where 15% and 25% replacement was below acceptable structural strength limit. Rubber size of 1mm-3mm provides acceptable compressive strength results when sand was replaced with 5% rubber for w/c of 0.35 to 0.25. However, it was decided that, in order and 0.71mm-1.7mm groups. Meanwhile, an increment in rubber percentage replacement

Table 3.2 Preliminary mortar flow result

w/c	Rubber replacement (%)	1mm - 3mm		0.71mm - 1.7mm		0.425mm	
		(sand replacement)		(sand replacement)		(cement replacement)	
		Mix No	Mortar flow (mm)	Mix No	Mortar flow (mm)	Mix No	Mortar flow (mm)
0.50	0	Control	164.50	Control	164.50	Control	164.50
0.40	0	A1	193.22	B1	193.22	C1	193.22
	5	A2	173.00	B2	144.27	C2	190.53
	15	A3	119.97	B3	no flow	C3	140.43
	25	A4	-	B4	no flow	C4	no flow
0.35	0	A5	150.42	B5	150.42	C5	150.42
	5	A6	131.98	B6	118.75	C6	no flow
	15	A7	108.74	B7	no flow	C7	no flow
	25	A8	no flow	B8	too dry	C8	-
0.30	0	A9	110.38	B9	110.38	C9	-
	5	A10	no flow	B10	no flow	C10	-
	15	A11	no flow	B11	no flow	C11	-
	25	A12	no flow	B12	no flow	C12	-
0.25	0	A13	no flow	B13	no flow	C13	-
	5	A14	no flow	B14	no flow	C14	-
	15	A15	no flow	B15	too dry	C15	-
	25	A16	no flow	B16	too dry	C16	-

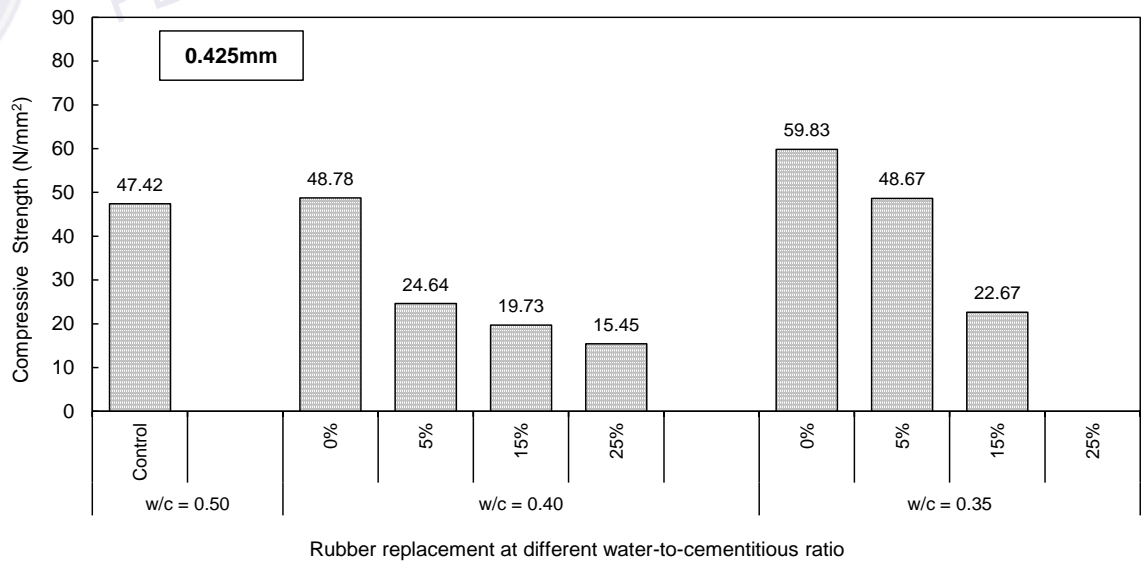
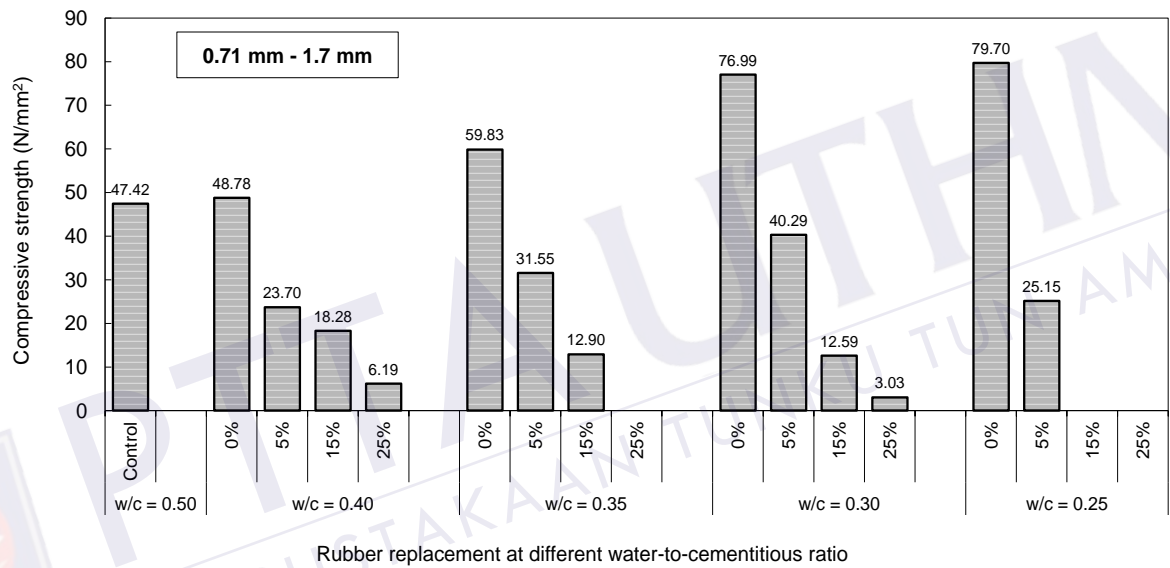
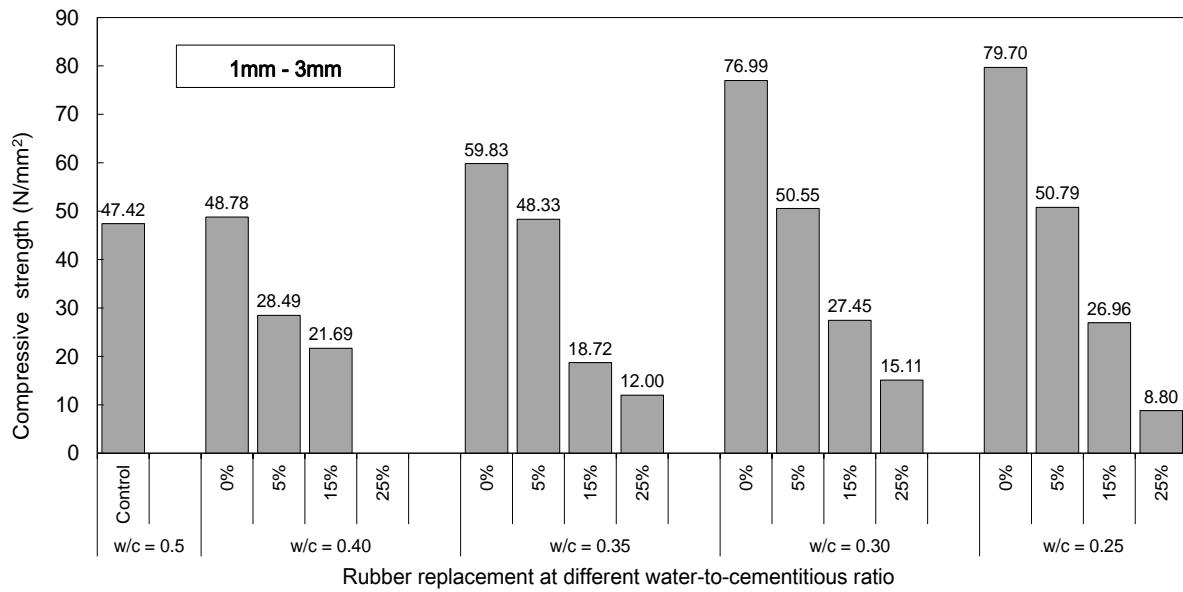


Fig. 3.4 Strength development of preliminary mortar mix at 28 water curing days.